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14. ABSTRACT The goal of this project is to understand how saccadic eye movements facilitate the performance of natural tasks. Saccades face conflicting demands: they must bring the line of sight to chosen targets quickly without drawing on the cognitive or attentional resources needed to recognize objects or formulate behavioral plans. Relying solely on visuomotor reflexes would minimize effortful planning, but risk drawing the eye to irrelevant locations. Careful planning would improve accuracy, but create excessive demands on cognitive resources. We have found that the dilemma is resolved by specialized processes that direct saccades to important locations with minimal cognitive load. These include: (1) strategies of planning saccadic sequences that favor increased scanning rate at the expense of careful target selection; (2) attentional filters shared with perception; (3) visual pooling mechanisms that automatically direct saccades to central locations within chosen objects. Experiments underway are examining (1) saccadic planning strategies in a complex search task, (2) attentional allocation accompanying sequences of saccades; (3) saccadic localization of shapes with a prominent "part" structure.

15. SUBJECT TERMS
(key words) saccadic eye movements; attention; planning; decisions; visual localization; adaptation; motor control; visual search.

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Overview

The overall goal of this project is to understand the planning and control of saccadic eye movements during the performance of complex visual tasks.

Saccadic eye movements are needed to bring the line of sight to important details. In order to serve this purpose effectively, saccades must reach the chosen destinations accurately and quickly, with minimal demands placed on the processing resources that are otherwise needed to recognize objects and formulate long-range behavioral plans. The requirements on saccades appear to conflict: saccadic plans, to be useful, must be derived from intelligent choices and decisions about where to look, but at the same time these plans must be formulated without requiring the attention and effort that is characteristic of high-level operations. Relying on automatic, built-in or stimulus-driven localization processes to program saccades would seem to be an effective way to reduce processing load. The problem is that too much stimulus control will occur at the expense of intelligent target selection, as the line of sight will be drawn to features of a scene that may be vivid, but nevertheless, irrelevant, to the goals and requirements of the task at hand. Relying exclusively on intelligent, thoughtful and rational planning has its disadvantages as well because people need to focus these cognitive resources on larger tasks, such as judging the contents of a scene or formulating global, long-range behavioral plans. Paying too much attention to saccades is a risky distraction.

How can the conflicting demands on saccades be resolved?

We have been studying a number of specialized mechanisms at various levels (cognitive, attentional, visual and motor) that allow saccades to reach important targets with minimal cognitive load. These include: (1) strategies of saccadic planning that favor increased scanning rate at the expense of careful target selection; (2) sharing of attentional filters with the perceptual system; (3) visual pooling mechanisms that automatically direct saccades to central locations within chosen (attended) objects; (4) adaptive control of saccadic accuracy by means of a comparison of predicted and obtained post-saccadic images. These processes allow saccadic eye movements to reach important targets quickly without need for effortful planning or the deliberate monitoring and control of the trajectory of each saccade.

Significance

The work is significant because it aims at achieving a basic understanding of the processes that control eye movements, and their interaction with visual and cognitive processes, which are essential for the successful acquisition of visual information in a wide range of natural and task-related situations. In addition, two specific areas of relevance can be noted:

(1) *Designing visual displays, tasks, instructions and training so as to produce best possible performance on tasks that are heavily dependent on eye movements.* Our work has particular relevance to performance under high demand situations, where time is limited and the consequences of errors are high. In those cases adopting effective eye movement patterns may be crucial to task success. Effective eye movement patterns depend on formulating and executing effective saccadic scanning patterns. We have found that the visual, attentional and motor systems are remarkably adept at executing plans, producing accurate saccades with a variety of visual displays. Saccadic "mistakes" are due primarily errors in planning, as careful, time-consuming planning is sacrificed in favor of increasing saccade rate. Efforts to improve planning should focus on structuring the displays, tasks and instructions so as to reduce the time needed to prepare saccades to important locations.

(2) *Design of artificial systems.* The human saccadic system has evolved a number of ingenious solutions to the problem of facilitating accurate scanning with minimal cognitive load. The solutions employed by the human system, if known, may be implemented in robotic systems which, like the human, have a limited field of fine detail vision and must allocate the field optimally within complex scenes.

Progress (January, 2002 - March, 2005)

Publications

Vishwanath, D. and Kowler, E. (2003) Localization of shapes: Eye movements and perception compared. *Vision Research*, 43, 1637-1653.

Vishwanath, D. and Kowler, E. (2004) Saccadic localization in the presence of cues to 3-dimensional shape. *Journal of Vision*, 4, 445-58.

Gersch, T., Kowler, E. and Dosher, B. (2004) Dynamic allocation of attention during sequences of saccades. *Vision Research*, 44, 1469-1483.

Under review:

Schnitzer, B. and Kowler, E. (2005) Eye movements during multiple readings of the same text. Vision Research (minor revisions requested and in preparation).

Denisova, K., Singh, M. and Kowler, E. (2005) The role of part structure in the perceived location of a shape. Perception (minor revisions requested and in preparation).

In progress:

Kowler, E. and Pavel, M. (2005) Optimal saccadic planning during visual search of multi-target arrays.

Melcher D. and Kowler, E. (2005) More than words: the accumulation of visual memory across separate glances

Summary of projects

1. Visual search (Kowler & Pavel, in progress).

Efficient performance of visual tasks requires that eye movements be directed to important locations quickly, but investing too much time and effort in target selection or saccadic planning risks taking resources from other cognitive activities. For example, important objects, relevant to the task, can be either far from the line of sight or hard to distinguish from the background. This inherent conflict between the importance of a target and the ease of accessing it makes it difficult to understand the rules and processes that govern natural saccadic planning. To investigate this conflict, we are studying saccadic planning during a visual search task in which the likelihood of obtaining useful information from different locations is pitted against the relative difficulty of reaching these locations.

In a prior study (Araujo, Kowler & Pavel; 2001) we used a 2-location search task, varying both the probability (disclosed by visual cues) that a location would contain the target, and the distance of the locations from the line of sight. Displays were available only briefly (500 msec), making the choice of the first saccadic target the crucial determinant of success. Surprisingly, 5 of the 6 subjects preferred to look at the closer location regardless of its probability level. Detailed examination of performance showed that they were not simply ignoring probabilistic information. Instead, they attempted a rapid sequence of two consecutive saccades, which often led them arrive at to the high probability (but more distant) location after the display was removed. This strategy was often preferred to the alternative of delaying the initial saccade an extra 20-50 msec, which would have allowed them to completely analyze the probability cue and direct the saccade in a way that would achieve search success. Thus, oculomotor athleticism was preferred to more patient, deliberate analysis (also, Melcher & Kowler, 2001).

Our new work with multi-location search (6 or 10 locations) allowed examination of longer saccadic sequences and revealed new saccadic characteristics. The display contained 6 clusters (3 red, 3 green) of 9 characters each with the target letter T embedded in one of the clusters (Fig. 1). The task was to find and report the orientation of the T. The probability of the T being located in either a red or green cluster varied from session to session so that the probability associated with one color was typically higher than that associated with the other. Displays of "mixed" clusters were also tested (Fig. 2). These were composed of either 6 ("mix6") or 7 ("mix7") characters of one color, with the remaining characters of the other color. With mixed clusters, the dominant color was harder to discern.

In multi-location search, the first saccade often ignored the probabilistic cues. Only two of the four subjects (JF and MG) made consistent use (proportion>.8) of the probability cue on the first saccade (Fig. 3). Even in their case, the proportion of first saccades landing on a high probability location rarely exceeded 0.8. Latencies of first saccades (Fig. 4) to high probability locations were about 20 ms longer than saccades to low probability locations for cases where the proportion of saccades reaching high probability locations was more than .8. In other words, selecting a high probability location was marginally costly in terms of programming time, and only JF (solid and mix7 clusters) and MG (solid clusters) opted to pay the price.

An examination of the dwell time of first saccades sheds more light on the search strategy. Fig. 5 shows that dwell times depended on the probability level of the cluster *currently* fixated, with longer dwell times for clusters with a greater chance of containing the target. Very brief dwell times (<100ms) occurred frequently (see distributions in Fig. 6) for saccades landing on low probability locations. These results have been confirmed for dwell times of saccades subsequent to the first saccade.

The brief dwell times were not due to a decision to abandon a useless cluster, but rather to the abrupt interruption of the fixation by the next saccade. The very brief dwell times suggests that programs for the second saccades in a pair were already underway even before the first saccade occurred. Moreover, most of these second saccades, unlike first saccades, did make use of the probability cue (see proportion of second saccades directed to high probability locations in Fig. 7). Thus, the saccadic sequence typically contained a rapid, useless fixation on a low probability cluster, interrupted by a delayed, but more useful, fixation on a high probability cluster. Producing such sequences took advantage of the saccadic system's ability to program saccades concurrently (Zing ale & Kowler, 1987).

These results have the following novel implication:

The long-standing conflict between whether saccades are attracted to objects based on their appearance (i.e., more "salient" high contrast objects attracting saccades) or high-level top-down strategies, is resolved by allowing both processes to contribute in parallel. The ability to program concurrent saccades allows useless fixations on salient objects to be terminated quickly by other, potentially more valuable fixations that took longer to program. Thus, rather than invoke potentially costly mechanisms to inhibit useless saccades, the saccadic system allows useless saccades to occur, but is able to move the eye quickly to other more valuable targets. The capacity to program saccades concurrently, and the option to relax the selectivity of individual saccades, go hand in hand to produce an effective pattern of action. Such scanning principles could be potentially of value in designing algorithms to drive artificial scanning systems that search visual environments.

Current direction: Pavel and I are determining how best to model the natural search patterns in this task and predict both the spatial and temporal characteristics of the saccadic pattern as a function of the probabilities and of the stimulus layout. The most promising approach may be to view the search task as a complex problem in saccadic localization (see #3, below) in which any saccade is a weighted average of the elements in the visual array. The weights for our search experiment would depend on factors such as probability and retinal eccentricity. For such an approach to accurately predict saccadic patterns it will be necessary to allow weights to change over time and to change depending on local spatial interactions among elements (McGowan, Kowler, Sharma & Chubb, 1998). An interesting aspect of this approach it separates the system characteristics that govern the changes in weight over space and time from the task-related factors (visual or cognitive) that determine the initial weighting.

2. Saccades and attention (Gersch, Kowler & Dosher,2004)

Selective attention designates which of the many possible objects in the visual field should be the goal of a saccadic eye movement. In an earlier series of experiments (Kowler, Anderson, Dosher & Blaser, 1995; also Bahcall & Kowler, 1999a) we asked whether saccades and perception share a common selective mechanism, or whether the filters operating for each are independent. We did dual task experiments that required observers to make a saccadic eye movement to one target while simultaneously identifying another. We found that it was difficult to perform the pair of tasks concurrently in that observers had to increase saccadic latency by about 20% in order to achieve accurate perceptual identification. These results show that saccades and perception share a common attentional mechanism. Nevertheless, the relatively small increase in latency needed to achieve accurate perceptual performance suggested that the attentional demands of saccades are relatively modest.

In a recently-completed set of experiments we extended these dual-task investigations to saccades made as part of sequences. There is evidence that sequences of movements (including saccades) are planned as a whole (Zingale & Kowler, 1987; Sternberg et al., 1978). This might lead to an increase the attentional cost of saccades early in the sequence, and a reduction in cost once sequence execution is underway.

We used a simple repetitive pattern of saccades that required observers to look in sequence at every other box in a display of 6 boxes (Fig. 8). During a randomly selected intersaccadic pause the perceptual target (a Gabor patch with superimposed visual noise) appeared briefly (91 ms) in one of the boxes whose location was cued at the outset of the trial. Although such cues improve the detectibility of the Gabor (assessed by contrast threshold for orientation discrimination) during maintained fixation, the outcome was quite different during intersaccadic pauses. Thresholds were elevated by about a factor of two relative to thresholds obtained during maintained fixation for all but two locations: the current locus of fixation and the location of the very next target (Fig. 9). The attentional advantages were confined to the goal of the very next saccade (saccade *n*), and did not apply to saccades further down in the sequence, (saccade *n+1*). These findings imply that spatial memory, not attention, is used to "mark" the location of saccades beyond the very next one in a sequence. We also found that the attentional advantage at the goal of the very next saccade was apparent early in the intersaccadic pause. In order for the attentional advantages to have emerged so quickly, the decision processes leading to attentional enhancement (such as retrieval of information about the saccadic goal) had to have occurred before a given saccade was completed (see also Visual Search, above). This points to a tight linkage between spatial memory, attention and saccadic programming in which programming and execution of saccade *n* may automatically initiate retrieval of the planned target for saccade $n+1$.

Our results are a significant step on the way to understanding the operation of vision, attention and memory during active scanning. Our findings suggest that a major function of extrafoveal attention is to guide the generation of accurate saccadic programs by establishing the target of the saccade. This role for attention is so important that it is carried out even at the expense of visual resolution at different places in the array. If attentional resources are concentrated on the support of saccadic plans, then attentional surveys of the scene to identify potentially interesting places to look are likely to be rare, and choice of saccadic targets would have to be carried by processes that place little or no demand on attentional resources.

3. Saccadic localization of objects (Vishwanath & Kowler, 2003, 2004)

Saccadic plans specify which objects to look at, but the saccades themselves must land at a single location within the chosen object. Presumably, the guidance of saccades to a location within the chosen object rests on lower-level visual or visuomotor processes, and not deliberate effort. We have studied saccades made to spatially-extended objects and found that saccades land near the center-of-gravity of the shape with a high-level of precision, unaffected by internal distributions of luminance or texture (Kowler & Blaser, 1995; McGowan et al., 1998; Melcher & Kowler, 1999; Vishwanath et al., 2000; for other aspects related to saccadic planning, see Bahcall & Kowler, 1999b, 2000).

Finding that saccades land near the center-of-gravity implies that the landing position is determined by averaging locations across the shape. In order to test this idea, Vishwanath & Kowler (2003) studied the landing positions of saccades directed to objects that were convex or concave. Concave objects (e.g., objects shaped like the letters C or L) are interesting because the center-of-gravity lies outside the shape. Thus, with such targets it is possible to find out whether the landing position is determined by averaging locations within the shape, in which case the eye would land outside the shape, near the center-of-gravity, or whether averaging is irrelevant and the eye is drawn to a prominent location within the borders of the shape.

The results of the experiments showed that saccades directed to concave shapes landed near the center-of-gravity (Fig. 10). Comparable perceptual localization tasks also showed a preference to use the COG as the reference point when evaluating the distance between shapes.

In follow-up experiments (Vishwanath & Kowler, 2004), landing positions were measured for objects that were drawn using perspective cues so that the objects would appear 3-dimensional on the screen. Of the 5 subjects tested, all perceived the shapes as 3D, but only two landed at the COG of the inferred 3-dimensional shape while the other three landed at the COG of the 2-dimensional image as drawn on the screen (Fig. 11). Scatter of landing positions was low for each group, indicating that each was equally consistent in the representation used to guide the saccades. It is possible that despite the individual differences, the same process -- averaging of locations within the retinal distribution of the shape -- determines landing positions. In that case differences among subjects could be due to assignment of different weights to different portions of the image. Assigning equal weights across the image would produce a landing position at the 2D COG, whereas assigning relatively more weight to the part of the shape perceived as lying furthest away would bias saccadic landing position toward the 3D center of gravity. There is support for such re-weighting from neurophysiological studies showing effects of distance on firing rates in V1 (Dobbins et al., 1998).

Data collection is nearly complete for a new set of studies on the effects of part-structure on saccadic localization (Kowler and Singh). Target shapes will be variants of an "L" in which the relative sizes of the limbs will be varied so that the center of gravity of the whole shape will differ from the average center-of-gravity of the 2 limbs. We want to find out whether the part-structure of shapes, which is prominent perceptually, is relevant to saccadic localization. Experiments will be done to determine (1) the effect of part structure on landing position of saccades directed to the shape as a whole, and (2) whether it is possible to aim saccades accurately to selected parts of shapes, without interference from the remaining, nonselected parts. These experiments will be useful for specifying the representation of shape and objects that is used to guide movements of the eye.

Saccadic localization that is accurate, fast and effortless is crucial for performance of real-world tasks requiring frequent changes in eye position. Robots or other scanning devices with moveable sensors also have to change the point of "fixation" accurately without excessive load on resources. Human beings are clearly very good at using saccades accurately and effortlessly. Our experiments on saccadic localization should be valuable in understanding the representations and computational rules that make this high level of performance possible.

4. Reading text repeatedly (Schnitzer & Kowler, 2005)

Effective reading depends on eye movements. Although the reading pattern is fairly stereotypical (successions of rightward saccades followed by resets to the next line), the factors that determine landing positions of individual saccades are not well understood. Analyses of landing positions show tendencies to land on average slightly to the left of center of words. To investigate the control of landing positions, we studied reading of the same text multiple times. We did this because all of what is known about reading eye movements has come from pooling data across individual subjects who read texts only once. An investigation of repeated reading of the same text would be useful to determine whether factors associated with the text were strong enough to produce consistent landing positions, or whether trial to trial variability, due to variability in visual or cognitive analyses each time a text is read, overcomes text characteristics, producing little consistency in landing positions.

In the experiment a given text was read 36 times, usually about 4 times/experimental session. Four different texts were used, and these were interspersed with new texts, seen only once in the experiment. Figure 12 shows landing positions of individual forward saccades of one representative subject. Clustering is prominent. Clustering at particular character locations did not occur for the texts read only once, showing that the clustering with repeated text was due to the effect of local text characteristics, and not to stereotypical saccade sizes. The locations of clusters varied, with clusters usually at the beginning and end of lines, and often (though not always) near the center of words. Clusters were prominent near the center of short phrases, indicating that repeated reading produces a tendency to group words and aim for the group. This finding suggests that the units guiding reading saccades are not fixed characteristics of text (e.g., word boundaries) but rather more flexible "recognition units", which might be a single word, portion of a word or a pair of words.

5. Part structure and perceived location (Denisova, Singh & Kowler, 2005)

We used a perceptual illusion originally reported by Morgan et al. (1990) to estimate the perceptual center of shapes with part-structure. The perceptual illusion reported by Morgan et al. showed that it is not possible to accurately estimate the distance between small targets placed inside circles. The distance judgments show an influence of the surrounding circle, as if the small targets were perceived as being located close to the center-of-gravity of the circle. As noted above, saccades directed to objects, including objects with part-structure, land near the center-of-gravity. Denisova et al. found that the illusion was substantially weaker when the circle was replaced with a bell shape composed of two distinguishable parts. The results suggest t hat unlike saccades, which are drawn reliably to a single location near the COG, the perceived center of objects is not necessarily the COG, but instead varies with the structure of the object.

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Figure 1. Searching for the T. The first saccade is shown in pale blue. The probability of the T being located in a red cluster was .8.

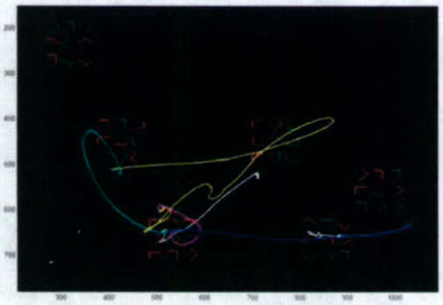

Figure 2 Searching for a T in mixed clusters.

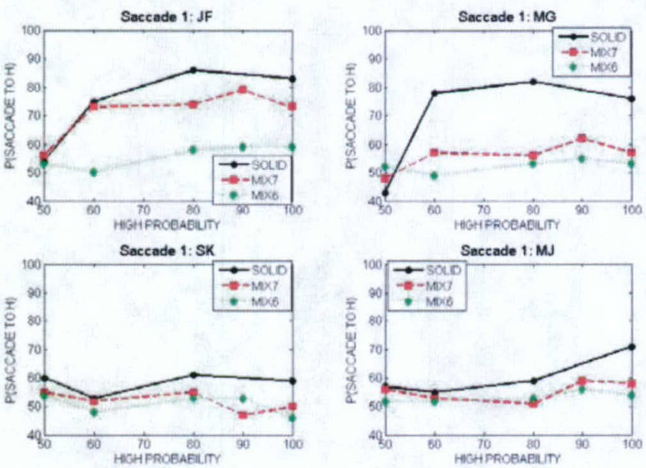

Figure 3. Proportion of first saccades to high probability clusters as a function of probability level.

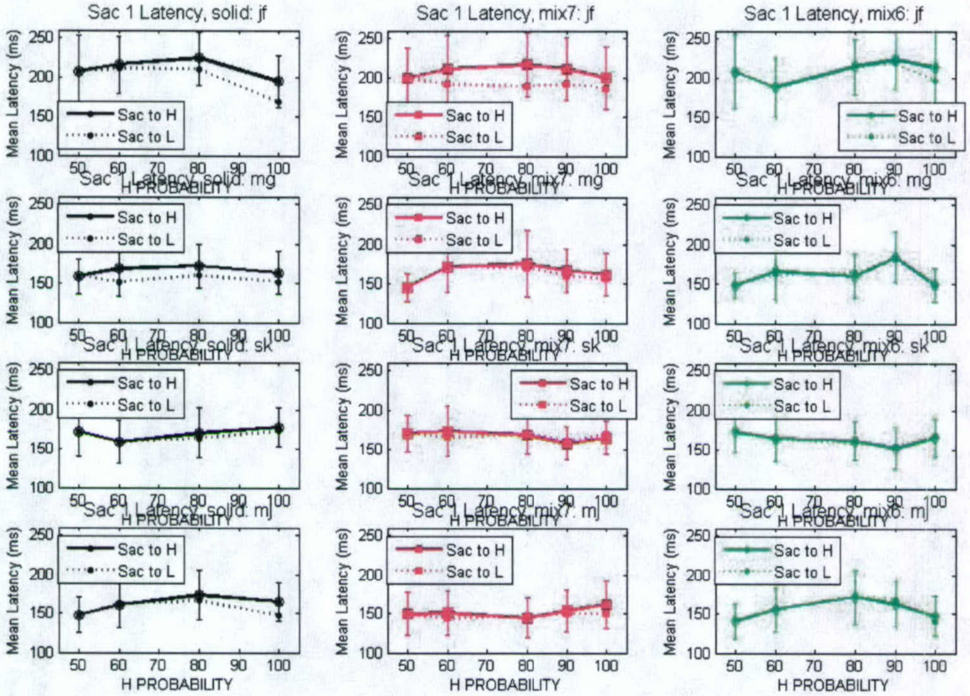

Figure 4. Latencies of first saccades to High and Low probability clusters.

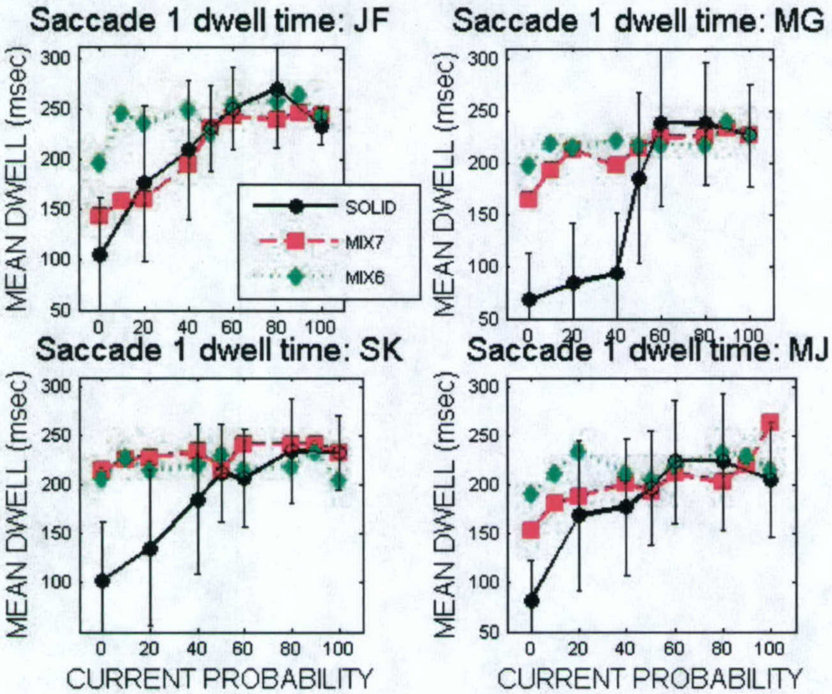

Figure 5. Dwell time of first saccade as a function of the probability of the fixated cluster.

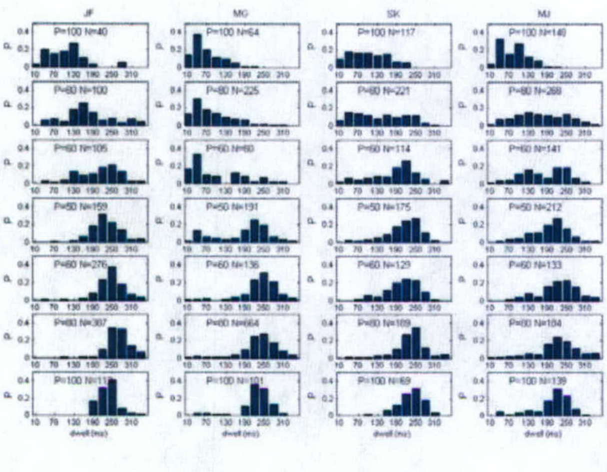

Figure 6. Histograms of dwell times of first saccade for search of SOLID clusters.

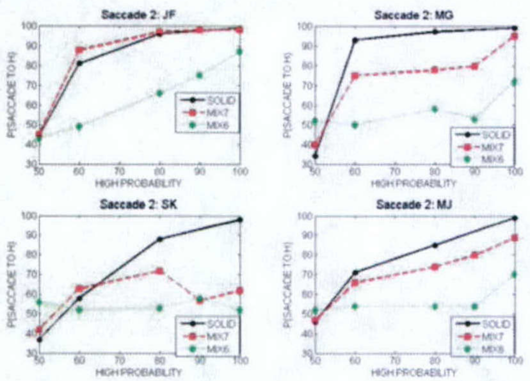

Figure 7. Proportion of second saccades directed to high probability clusters as a function of the high probability level.

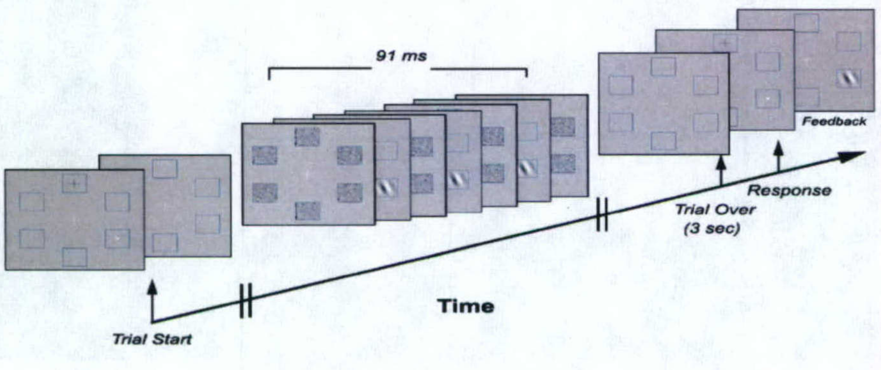

Figure 8. Sequence of frames. The first (cue) frame indicates starting fixation position (black cross) and location of Gabor (small white square). Saccades to every other box were signaled by a tone 100 ms after trial start. Gabor+noise frames were presented during a randomly selected intersaccadic pause, and appeared superimposed during the trial.

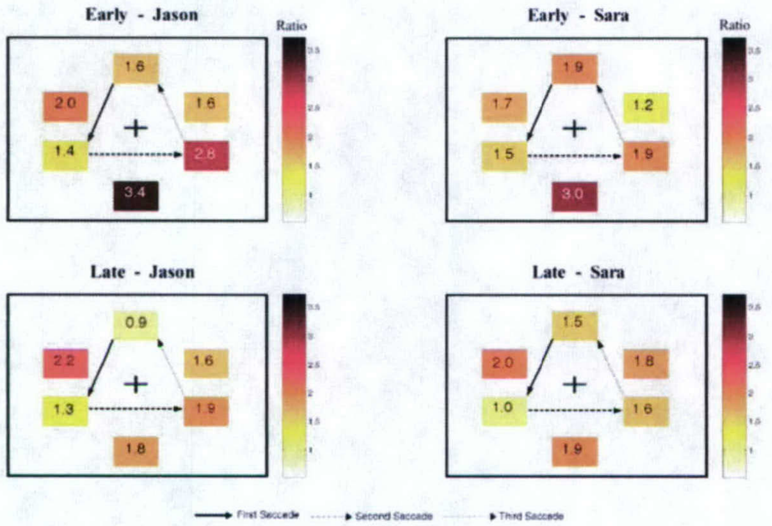

Figure 9. Ratio of contrast thresholds during intersaccadic pauses to contrast thresholds during steady fixation. Values over 1 indicate that visual sensitivity is reduced at selected locations during intersaccadic pauses. The current fixation position is represented at the topmost square. The target of the next saccade in the sequence is represented at the bottom left and the target of the following saccade at the bottom right.

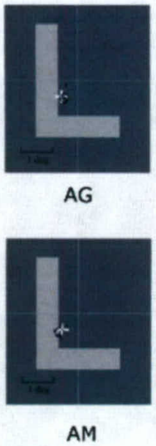

Figure 10. Mean landing positions of saccades directed to the target "L" from an eccentricity of 4 degrees. Landing positions coincide with the center-of-gravity (white cross). Individual data points show results with different orientations of the L; the open circle is the mean of the individual means.

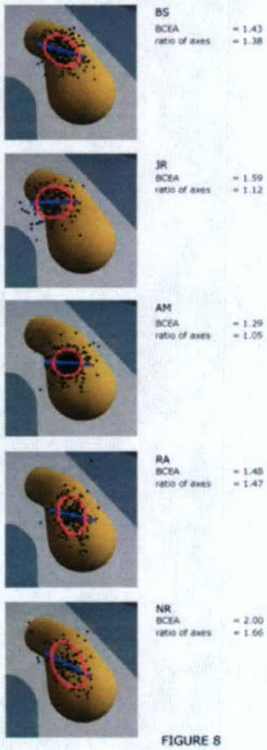

Figure 11. Landing positions of saccades on shapes constructed to appear 3D. Subjects BS and JR landed near the 3D center-of-gravity of the implied object while the others landed near the 2D center of gravity of the retinal projection. BCEA=bivariate contour ellipse area.

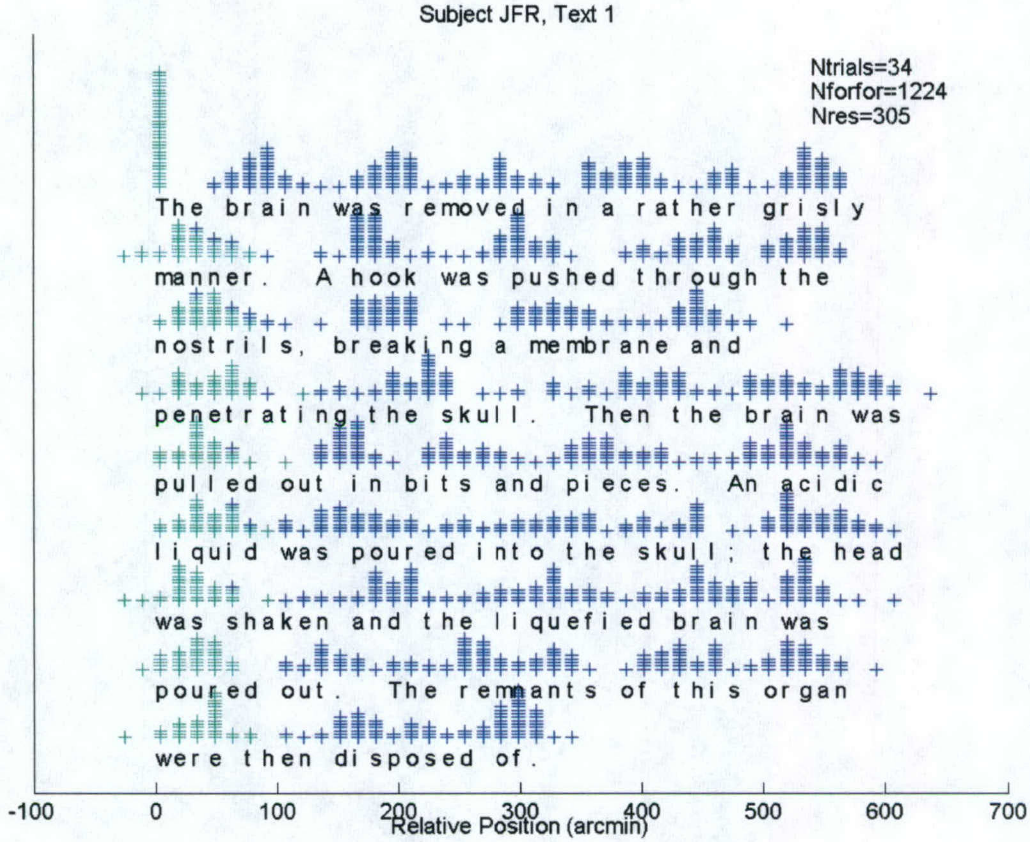

Figure 12. Landing positions of individual saccades of subject JFR during repeated (N=68) readings of the same text. Green symbols are initial landings on each line. Some clusters are centered on words, others on phrases (e.g., line 2: was pushed; line 6: was poured)